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Estimation of urban solar radiation for the City of Recife-PE

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ABSTRACT

Urban Global Solar Radiation(RS) is one of the main inputs of urban climatology, and should already be considered from the conception of the construction project of green infrastructures, which mitigate the environmental impacts of urbanization. The objectives of this work were to calibrate and evaluate the performance in estimating the RS, for the capital of Pernambuco, of six existing models in the literature, namely: Hargreaves; Samani (1982), Bristow; Campbell (1984), Jong & Stewart (1993), Chen et al. (2004), Hunt et al. (1998) e Annandale et al. (2002), referring to a rainy period in the year 2023, with data from an automatic meteorological station installed in one of the campuses of the University of Pernambuco, in the city of Recife-PE. The statistical criteria used for the analysis of the calculated data: the root mean square error (RMSE), the Nash-Sulcliffe coefficient (NSE) and the residual mass coefficient (CMR). The models, in ascending order of greater effectiveness are: Hunt et al. (1998), Bristow; Campbell (1984), Jong & Stewart (1993), Chen et al. (2004), Hargreaves; Samani (1982), and Annandale et al. (2002). However, it should be noted that for the use of the model proposed by Hunt et al. (1998), it is necessary to have daily precipitation data, which may not be available, especially in historical series. If only temperature values are available, the best model for estimating RS is the one proposed by Bristow; Campbell (1984), which presented a satisfactory performance and very close to that obtained by the model proposed by Hunt et al. (1998).

KEYWORDS: Evapotranspiration. solar radiation. Green infrastructures.

1 INTRODUCTION

Green infrastructure (GI) construction mitigates the impacts of urbanization, utilizing components of the hydrological cycle to reduce runoff volume. In most GI techniques, such as rain gardens, infiltration is the primary mechanism for stormwater control, while in a green roof, water is retained in its soil and the restoration of infiltration capacity is regulated by evapotranspiration, which significantly depends on solar radiation (SR).

SR is a key input in urban climatology and should already be considered in the design of construction projects. It should influence decision-making regarding building orientation, height, acceptable glass coverage percentage, and climate conditioning requirements of buildings. Solar radiation also plays a significant role in the thermal comfort of city residents. The differential heating of the city and its surroundings, while complex, is partially responsible for the creation of the urban heat island and associated convection cells, with considerable implications for air pollution.

The entire spectrum of SR (diffuse solar radiation and direct solar radiation) can be measured using a specific radiometer called a pyranometer, which is found in many modern meteorological stations. However, due to the costs of acquiring and maintaining these sensors, their use is not widespread in most meteorological stations, especially government-owned ones (JAHAN; AKHTAR, 2017).

Thus, some researchers have developed empirical methods to estimate SR based on more easily available data from meteorological stations, such as air humidity (YANG; KOIKE, 2002), precipitation (HUNT et al., 1998; LIU; SCOTT, 2001; RIVINGTON et al., 2005), cloudiness (DAVIES; MCKAY, 1989; MUNNER; GUL, 2000), sunshine duration (ANGSTRÖM, 1924; WONG; CHOW, 2001; ALMOROX; HONTORIA, 2004; CHEN et al., 2006), and daily temperature range (HARGREAVES, 1981; HARGREAVES; SAMANI, 1982; BRISTOW; CAMPBELL, 1984).

These models have been adapted and/or modified by other researchers, attempting to improve the estimates in different locations over time. However, it is worth noting that empirical models should be locally calibrated, as empirical relationships vary spatially. Ramos et al. (2018) emphasize that despite the improvement in estimates of global solar radiation after calibration, these models should be optimized for each season of the year to minimize potential seasonal effects in each region. Models that estimate SR typically use sunshine duration, temperature, and other meteorological variables such as cloudiness index (BESHARAT et al., 2013). However, incorporating all these parameters simultaneously complicates the empirical correlation, and usually only a subset of parameters is used in the developed models (GUREL et al., 2023).

Models estimating SR based on sunshine duration are more accurate than those estimating it from air temperature and precipitation; however, sunshine duration data are rarely found in meteorological stations in general (ALMOROX, 2011). Nonetheless, sunshine duration data are not present in many of the existing meteorological stations in Brazil. Therefore, proposed methods typically rely on air temperature and precipitation and stand out as viable alternatives, especially when analyzing urban SR values.

While SR has been extensively studied in agricultural regions, few studies have evaluated it in urban areas or developed specific appropriate models for these environments. Moreover, in several Brazilian cities (such as Blumenau - SC, Porto Alegre - RS, Guarulhos-SP, and João Pessoa-PB), the construction of green roofs has become mandatory in new buildings to minimize flooding. In Recife-PE, this requirement came into effect in 2015 (Law No. 18.112, 2015, Art. 1). However, in many projects and studies, SR is either not considered or estimated using empirical equations that do not accurately reflect the local reality.

In this context, the importance of studying global solar radiation in urban areas is emphasized, and it is essential to define appropriate models for its estimation, which may differ from those suitable for vegetated regions.

2 OBJECTIVES

The objectives of this work were to calibrate and evaluate the performance in estimating urban Global Solar Radiation for the capital of Pernambuco state, using six models existing in the literature. These models were applied to a rainy period in the year 2023, using data from an automatic meteorological station installed on one of the campuses of the University of Pernambuco, in the city of Recife, Pernambuco, Brazil.

3 METHODOLOGY

The study was conducted in the city of Recife, the capital of the state of Pernambuco, located at the coordinates: latitude 8° 04' 03" S and longitude 34° 55' 00" W, with an altitude of 4m. This coastal city covers a land area of 218.50 km². For the execution of this study, data on air temperature, precipitation, and solar radiation were utilized, collected during the period from May 18th to July 10th, 2023. The data were acquired through an automatic meteorological station of the Davis brand, installed on the premises of the Polytechnic School of Pernambuco (POLI). Initially, the data were collected at 10-minute intervals and later summarized into daily values, including maximum ($T_{máx}$) and minimum ($T_{mín}$) temperature, total incident solar radiation (RS), and rainfall (P) for each day.

Subsequently, the data underwent a consistency assessment based on the elimination criteria proposed by Liu et al. (2009), which are as follows: a) missing data for any of the elements $T_{máx}$, $T_{mín}$ ou RS; b) $T_{máx} < T_{mín}$; c) $RS/RA > 1$. Daily cloudiness, defined by the clearness index (I_k), was determined by the relationship:

$$I_k = RS/RA \tag{1}$$

Where RA represents the solar radiation at the top of the atmosphere, and I_k is classified according to Table 1.

Tabela 1 – Classification of daily cloudiness

I_k	Classification
$0 \leq I_k < 0{,}3$	Cloudy sky
$0{,}3 \leq I_k \leq 0{,}65$	Partly cloudy sky
$0{,}65 < I_k \leq 1$	Clear sky

Source: Auler; Minuzzi (2022)

3.1 Models evaluated

The models analyzed for estimating global solar radiation (RS) are presented in Table 2 and include: Hargreaves; Samani (1982), Bristow; Campbell (1984), Jong; Stewart (1993), Chen et al. (2004), Hunt et al. (1998), and Annandale et al. (2002). All of these models utilize as input data the solar radiation at the top of the atmosphere (RA) and the daily thermal amplitude (difference between the maximum and minimum daily temperatures).

The model proposed by Hargreaves; Samani (1982) estimates global solar radiation in a linear manner. It includes a regional adjustment parameter that depends on local climatic conditions. The authors recommend values of 0.19 and 0.16 for coastal and continental regions, respectively. The model proposed by Chen et al. (2004), like Hargreaves; Samani (1982), employs a linear relationship by considering the linear coefficient of the line. As such, this model has two adjustment parameters.

Bristow; Campbell (1984) proposed a model that estimates RS exponentially, utilizing three regional adjustment parameters (α, β, and γ). While empirical, α represents the maximum expected transmissivity for a clear sky day, which depends on altitude and local atmospheric pollution. On the other hand, coefficients β and γ control the variation of α with respect to thermal amplitude. For parameters α and γ, the recommended values are 0.7 and 2.4, respectively. For β, the recommended value is 0.004 for dry periods and 0.01 for wet periods.

Jong; Stewart (1993) proposed a model that introduces the effect of precipitation in estimating RS in a multiplicative manner. It involves four adjustment parameters. Hunt et al. (1998) also presented a model considering precipitation, but in a non-multiplicative way, also containing four adjustment parameters.

Annandale et al. (2002) proposed a model with one adjustment parameter and introduced an altitude correction for RS. They recommended a value of 0.16 for inland locations where land masses dominate and air masses are not strongly influenced by large bodies of water. For coastal locations situated on or adjacent to the coast of a significant landmass, where air masses are influenced by a nearby water body, the recommended value is 0.19.

Table 2 - Models Evaluated for Solar Radiation Estimation

Abbreviation (reference)	**Model**
RSHS (Hargreaves; Samani 1982)	$RS_{HS} = RA \cdot k_t \cdot (T_{máx} - T_{mín})^{0.5}$
RSBC (Bristow; Campbell 1984)	$RS = RA \cdot \alpha \cdot (1 - e^{-\beta \cdot (T_{máx} - T_{mín})^{\gamma}})$
RSJS (Jong & Stewart 1993)	$RS = \alpha(T_{máx} - T_{mín})^{\beta}(1 + \gamma P + \delta P^2)RA$
RSCH (Chen et al., 2004)	$RS = [\alpha(T_{máx} - T_{mín})^{0.5} + \beta]RA$
RSHU (Hunt et al., 1998)	$RS = RA \cdot \alpha \cdot (T_{máx} - T_{mín})^{0.5} + \beta\, T_{máx} + \gamma P + \delta P^2$
RSAN (Annandale et al. 2002)	$RS = \mathrm{RA} \cdot \alpha(1 + 2.7 \cdot 10^5 Alt)(T_{Máx} - T_{Mín})^{0.5}$

Where *RS* and *RA* are the incident solar radiation at the surface and the top of the atmosphere (MJ m^{-2} d^{-1}); AAlt is the local altitude (m); $T_{máx}$ e $T_{mín}$ are the maximum and minimum temperatures of the day (°C); P is the precipitation (mm); and α, β, γ, and δ are coefficients of adjustment for empirical models (dimensionless).

3.3 Daily solar radiation at the top of the atmosphere

The daily solar radiation at the top of the atmosphere, *RA* (MJm^{-2}day^{-1}) as determined by the equations below:

$$RA = 24 * \frac{60}{\pi} G_{sc} d_r [\omega_s sen(\phi) sen(\theta) + \cos(\phi)\cos(\sigma)\sin(\omega_s)] \quad (2)$$

Where G_{sc} s the solar constant (0,082 MJ$m^{-2}$$d^{-1}$), J is the day of the year, d_r is the inverse of the relative Earth-Sun distance, ω_s s the solar hour angle (rad), φ is the latitude (rad), and σ is the solar declination (rad), calculated by equations 2 to 4:

$$d_r = 1 + 0{,}033\cos\left(\frac{2\pi J}{365}\right) \quad (3)$$

$$\sigma = 0{,}409 sen\left(\frac{2\pi J}{365} - 1{,}39\right) \quad (4)$$

$$\omega_s = \frac{1}{\cos(-\tan(\phi)\tan(\sigma))} \quad (5)$$

3.4 Model Adjustment and Performance

Three statistical criteria were used for the analysis of the calculated data: the root mean square error (*RMSE*), the Nash-Sutcliffe coefficient (*NSE*), and the residual mass coefficient (*CMR*).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(RS_{obs} - RS_{est})^2}{n}} \quad (6)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(RS_{obs} - RS_{est})^2}{\sum_{i=1}^{n}(RS_{obs} - \overline{RS_{obs}})^2} \quad (7)$$

$$CMR = \frac{\sum_{i=1}^{n} RS_{obs} - \sum_{i=1}^{n} RS_{est}}{\sum_{i=1}^{n} RS_{obs}} \quad (8)$$

Were $\overline{RS_{obs}}$ the mean of the observed RS, n being the number of observed values, RS_{obs} and RS_{est} epresenting the observed and estimated RS values, respectively.

The RMSE varies between 0 and infinity (∞), where lower values indicate better RS estimation. The NSE ranges from $-\infty$ a 1 and values closer to 1 represent more accurate results. Values between 0 and 1 are generally seen as acceptable performance levels, while values below 0.0 indicate that using the mean of observed data is better than the predicted model value. NSE values above 0.0 can be interpreted according to Table 3 (Nash; Sutcliffe, 1970). The CMR indicates whether the model overestimated (CMR < 0) or underestimated (CMR > 0) the observed values.

Table 3 – Classification of NSE values

NSE	Classification
$NSE < 0,5$	Unsatisfactory
$0,5 \leq NSE < 0,65$	Satisfactory
$0,65 \leq NSE < 0,75$	Good
$0,75 \leq NSE \leq 1$	Very Good

Source: Lin et al. (2017), Boldrin et al., (2022).

4 RESULTS

The average RS for the studied period was 12.10 $MJm^{-2}d^{-1}$. As expected, this value is lower than the annual average reported by Ramos et al. (2018) for Recife, which was 22,18 $MJm^{-2}d^{-1}$ assessing SR for 32 Brazilian cities between 1999 and 2012. This lower value is attributed to the study considering only the rainy period for the location, during which there was rainfall on all days except one.

During the period evaluated in this study, there were no clear sky days (I_k > 0.65). On 75.5% of the days, the sky was partly cloudy ($0,3 \leq I_k \leq 0,65$), and on 24.4% of the days, the sky was classified as cloudy ($0 \leq I_k < 0,3$). In Table 4, you can find the values of position and dispersion measures for daily precipitation in Recife on cloudy and partly cloudy days. Rainfall was much more consistent on cloudy days, with an average value of nearly 60 mm. This is significantly higher than the average rainfall on partly cloudy days (8.90 mm). Unexpectedly, there was a day of partly cloudy sky with precipitation exceeding 60 mm.

Table 5 shows the adjusted coefficients of the analyzed models for the city of Recife, Pernambuco. Following the adjustments, the models displayed good coefficients of determination (R^2), with results ranging from 0.62 to 0.71. Hence, it can be stated that these models exhibit an efficiency of over 62% in estimating solar radiation. In this study, the model adjustments were performed using the least squares method.

Table 4 - Measures of central tendency and dispersion of daily precipitation for Recife during the study period.

	Daily precipitation	
	Partly cloudy sky	Cloudy sky
Minimum	0,00 mm	3,80 mm
Maximum	61,80 mm	122,80 mm
Mean	8,90 mm	58,67 mm
1st Quartile	0,60 mm	25,20 mm
Median	2,60 mm	74,80 mm
3rd Quartile	13,05 mm	82,30 mm

The models with the highest R^2 values, in order, were RSHU, RSJS, RSBC, RSCH, SAAN, and RSHS. Similar findings were reported by Boscaini et al. (2019) for the municipality of Santa Maria, RS, where they calibrated and evaluated the performance of ten different models for estimating daily solar radiation based on air temperature data for irrigation purposes. They used data from a meteorological station of the Brazilian National Institute of Meteorology (INMET). They concluded that, in general, after calibration of their coefficients, these models are recommended for use when locally observed solar radiation data is not available.

Table 5 - Empirical Parameters and Coefficients of Determination for Analyzed Models, After Optimization.

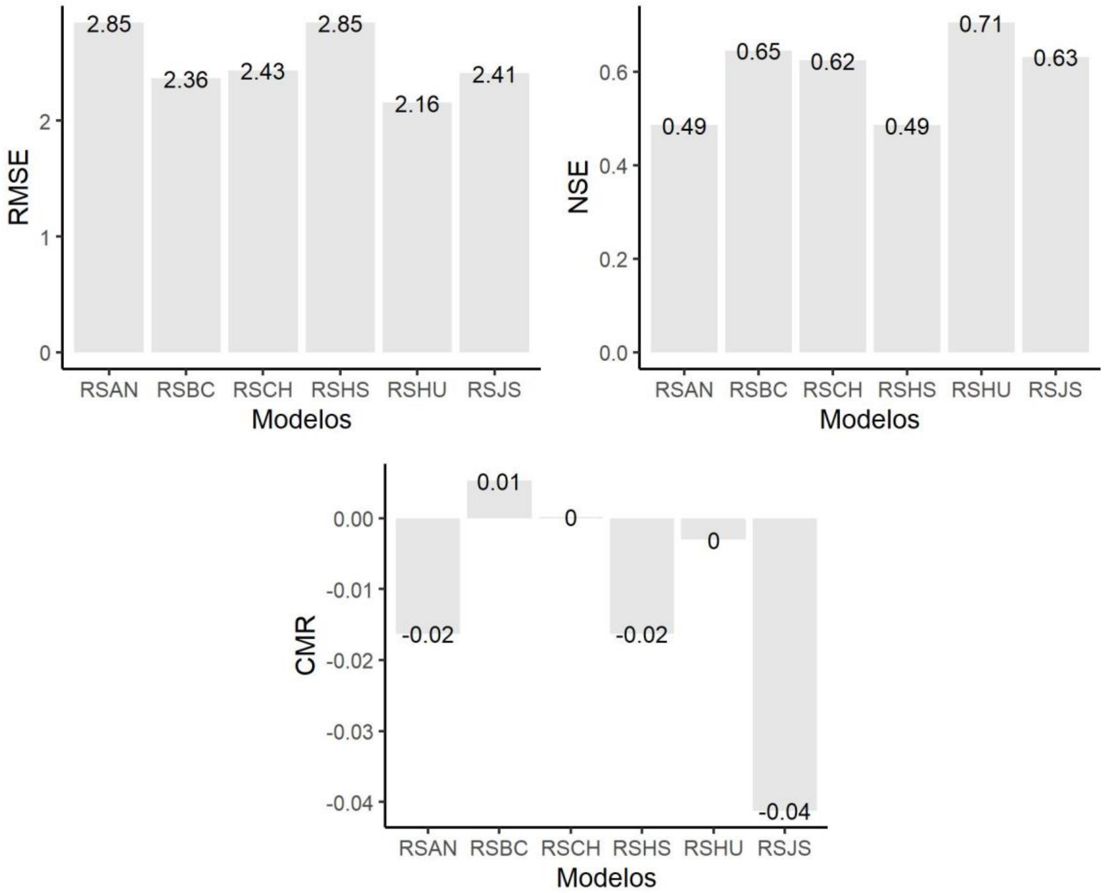
Model	Adjustment parameters				R^2
	α	β	γ	δ	
RSHS	0. 16767				0.62
RSBC	0.58819	0.02114	2.24156		0.65
RSJS	0.17600	0.51000	-0.00100	-0.00002	0.69
RSCH	0.31770	0.37367			0.62
RSHU	0.15229	-0.07546	-0.09224	0.00034	0.71
RSAN	0.16769				0.62

Based on the values of the Root Mean Square Error (RMSE) and the Nash-Sutcliffe coefficient (NSE), we can classify the evaluated models for the city of Recife, Pernambuco. Additionally, using the Coefficient of Residual Mass (CMR), we can identify which models underestimated or overestimated the observed SR values (Figure 1). Overall, all models exhibited satisfactory results. With the exception of the RSAN model, all models outperformed the RSHS model, which represents the oldest estimate. These results are consistent with the initial graphical analysis. For all models, the RMSE values ranged between 2 $MJm^{-2}d^{-1}$ e 3 $MJm^{-2}d^{-1}$, and the NSE values were between 0.49 and 0.71. Four models overestimated while two models underestimated the observed RS values.

Firstly, we have the RSHU model, which exhibited the lowest RMSE value (2.16 $MJm^{-2}d^{-1}$) and an NSE value of 0.71, closer to 1 among the analyzed models, thus classified as good. It is worth noting that this model employs daily precipitation values to estimate RS. This model demonstrated a slight overestimation concerning the observed global solar radiation values (CMR = -0.00272).

The second position was held by the RSBC model, which achieved an RMSE of 2,36 $MJm^{-2}d^{-1}$ and an NSE of 0.65, yielding a satisfactory outcome. This model estimates RS solely based on thermal amplitude in an exponential form, using three regional adjustment parameters. There was a slight underestimation of RS values by this model (CMR = 0.00801).

Figura 1 – Figure 1 - Root Mean Square Error (RMSE), Nash-Sutcliffe coefficient (NSE), and Coefficient of Residual Mass (CMR) for the adjusted models in the city of Recife, Pernambuco.



The third position was taken by the RSJS model, which, similar to the RSHU model, considers precipitation values in its calculations but in a multiplicative manner. The RMSE and NSE values were 2,41 $MJm^{-2}d^{-1}$ and 0.63, respectively, indicating a satisfactory performance. Here was a slight overestimation of RS values by the RSJS model (CMR = -0.03899). The fourth position was occupied by the RSCH model, with an RMSE of 2,43 $MJm^{-2}d^{-1}$ nd an NSE of 0.62. This model displayed a minor underestimation compared to the observed global solar radiation values (CMR = 0.00023).

The RSHS and RSAN models tied for fifth place, exhibiting equal performance in both RMSE (2,85 MJm-2d-1), and NSE (0.49), both of which were classified as unsatisfactory. Both models overestimated the observed global solar radiation values, with CMR values of -0.01560. This indicates that, for the specific location and during the rainy period, the inclusion of altitude in the model did not significantly affect the performance of RS estimates.

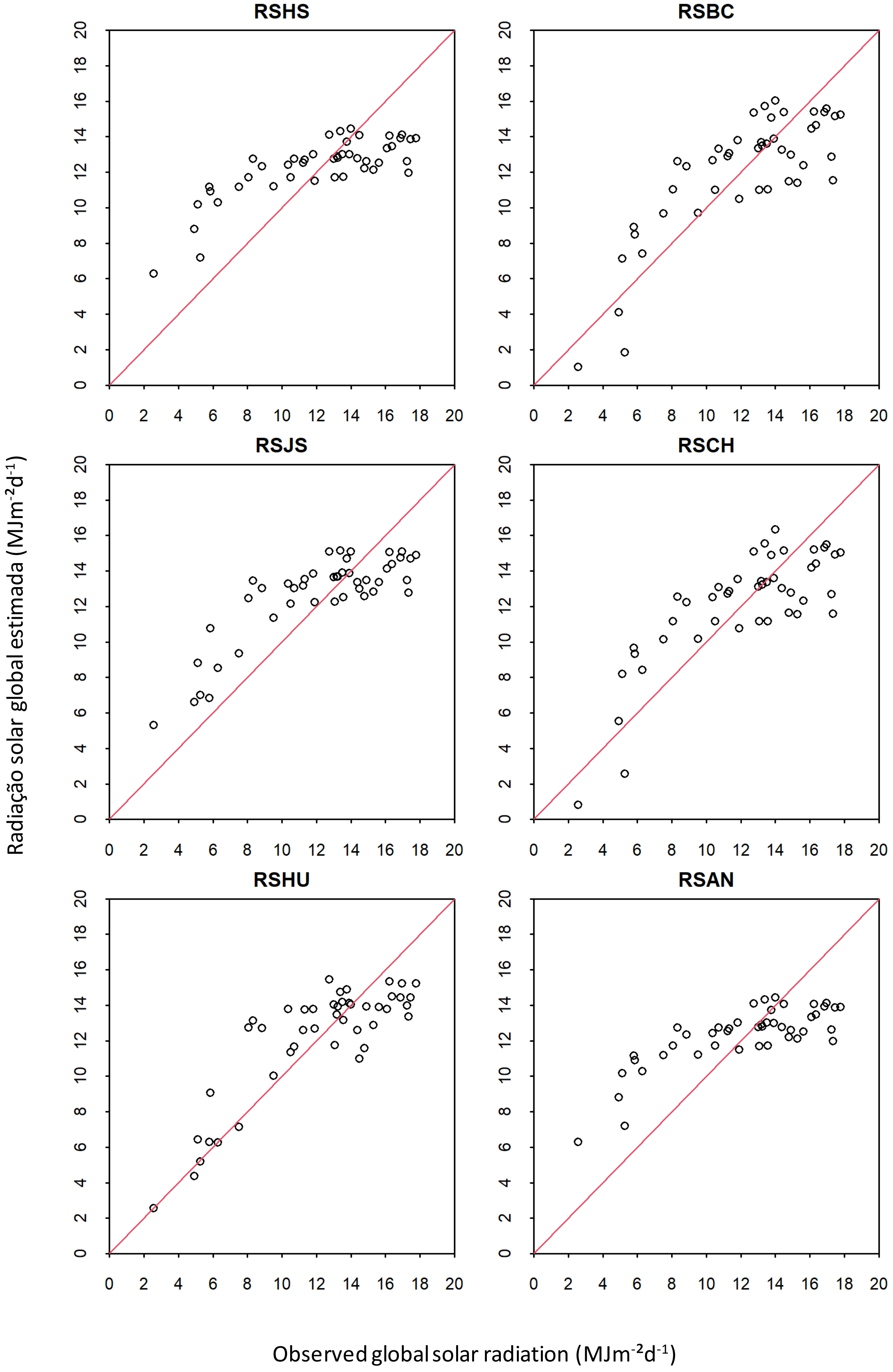
Silva et al. (2012), while estimating RS for the Northwest region of the State of Minas Gerais, found less favorable results when using the RSAN model. This model exhibited an R^2 of only 0.5 and an RMSE of 3,5 $MJm^{-2}d^{-1}$, when estimating RS values.

Mazzarella et al. (2019), while estimating daily RS using the Hargreaves-Samani model for the state of Rio de Janeiro, based on data from 11 meteorological stations, concluded that in general, the Hargreaves and Samani method is not satisfactory even after calibration for the climatic conditions of the area. It proved to be significant only when the data came from stations close to water bodies. In this study, the Hargreaves-Samani and Annandale et al. (2002) models were among the models with weaker performance, albeit still satisfactory. This may be attributed to the study area's proximity to a river.

Figure 2 depicts the values of estimated solar radiation plotted against measured solar radiation, utilizing the tested empirical models for the city of Recife, Pernambuco.

The primary advantage of this type of graph is its ability to quickly reveal the relationship between measured and estimated values, which should be close to the 1:1 line. Additionally, it allows for the identification of any anomalies present. It can be observed that all models presented estimated values of solar radiation within the same magnitude as the measured values (between 0 and 20). It's noticeable that the HSHA and HSAN models exhibited a higher number of points deviating from the 1:1 line compared to the others. Although it's not possible to determine solely through graphical analysis which of the other models performed better, the graphical results align with the statistical parameters used.

Figure 2 - Estimated solar radiation plotted against measured solar radiation using the tested empirical models for the city of Recife, Pernambuco.



5 CONCLUSION

After the calibration of parameters, the analyzed models have demonstrated their capability to estimate daily global solar radiation for the city of Recife, Pernambuco, and can be used when meteorological station data is lacking.

The performance of the models, ranked from highest to lowest efficacy, is as follows: Hunt et al. (1998), Bristow; Campbell (1984), Jong & Stewart (1993), Chen et al. (2004), Hargreaves; Samani (1982), and Annandale et al. (2002). However, it's important to note that using the model proposed by Hunt et al. (1998) requires daily precipitation data, which may not always be available, especially in historical datasets. If only temperature values are available, the best model to estimate RS is the one proposed by Bristow; Campbell (1984), which exhibited satisfactory performance and was very close to the performance achieved by the Hunt et al. (1998) model.

One factor to consider is that the evaluated models were calibrated only for the rainy season of 2023, which may have influenced their performances if it was an atypical year.

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